VOLUME XXVIII NUMBER 7

THE

JOURNAL OF GEOLOGY

OCTOBER-NOVEMBER 1920

THE KATMAI REGION, ALASKA, AND THE GREAT ERUPTION OF 1912

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In June, 1912, Mount Katmai was the scene of one of the greatest volcanic eruptions known in history. The material ejected, mostly in the form of pumice and fragmental glass, formed deposits whose total volume has been calculated to amount to nearly five cubic miles.[1] At the town of Kodiak, a hundred miles away, this fragmental material ("ash") fell to the depth of nearly a foot, and nearer to the volcano hundreds of square miles of territory were completely devastated.

General knowledge of the effects of this eruption has been derived chiefly from the explorations of several expeditions sent out by the National Geographic Society, the first one under G. C. Martin and later ones under R. F. Griggs.[2] The expedition of the summer of 1919 was planned on a considerably more ambitious scale than former ones, and an invitation was extended to the Geophysical Laboratory to co-operate in the scientific work.

[1] G. C. Martin, "The Recent Eruption of Katmai Volcano in Alaska," *National Geographic Magazine*, Vol. XXIV (February, 1913), No. 2, p. 131.

[2] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV. (February, 1913), No. 2, p. 131; R. F. Griggs, *Nat. Geog. Mag.*, Vol. XXXI (January, 1917), No. 1, p. 13; and Vol. XXXIII (February, 1918), No. 2, p. 115; *Ohio Journal of Science*, Vol. XIX (1918), p. 2.

Under this arrangement E. T. Allen, E. G. Zies, and C. N. Fenner joined the party for the purpose of studying the chemical and geological phenomena. Previous to our departure for the Katmai region the publications of Dr. Martin and of Professor Griggs and the information obtained from conversations with them were of much assistance to us in making plans for the trip, and, while we were on the ground, Professor Griggs's knowledge of the region and its phenomena continued to be of great service. The party spent about two months and a half in the field, which is about as long a working season as is practicable.

Since the return to Washington, much time has been given to the study of the materials collected, and a full report will be published later. In advance of such publication, however, it has been thought that a shorter article, descriptive of some of the features of chief geologic importance, may be of interest, and is here presented. Necessarily in this brief treatment, many matters to which attention has been paid in our work will be omitted entirely, and in the case of others the basis for conclusions will be presented in brief form only. Fuller discussion must be reserved for the more comprehensive articles to follow.

TOPOGRAPHY AND GENERAL GEOLOGY

The Katmai country is situated near the base of the Alaska peninsula—that long arm which extends southwestwardly from the southern shore of continental Alaska and, with the Aleutian Islands, reaches nearly to Kamchatka (Fig. 1).

Previous to the eruption of 1912, the Katmai region, though difficult of access, was not entirely unknown. On the Pacific side of the volcanic range was the small native village of Katmai, not more than twenty miles from the volcano. On the Bering Sea slope, at the head of Naknek Lakes, was the similar village of Savonoski. Between them ran a trail which had probably been traveled by the natives for many years, and more recently had been used fairly frequently by white men as a means of crossing the peninsula. In 1898 J. E. Spurr, of the United States Geological Survey, led a party over the Katmai trail, but observed nothing which might be considered to indicate that the preliminary pro-

cesses leading to the eruption were at work except that near the summit of the Pass the party experienced several earthquake shocks. Spurr's record[1] is of much value, however, for the information it gives on the general character of the country. Their route lay through the midst of the area that was subsequently devastated. Further reference to this report will be made later.

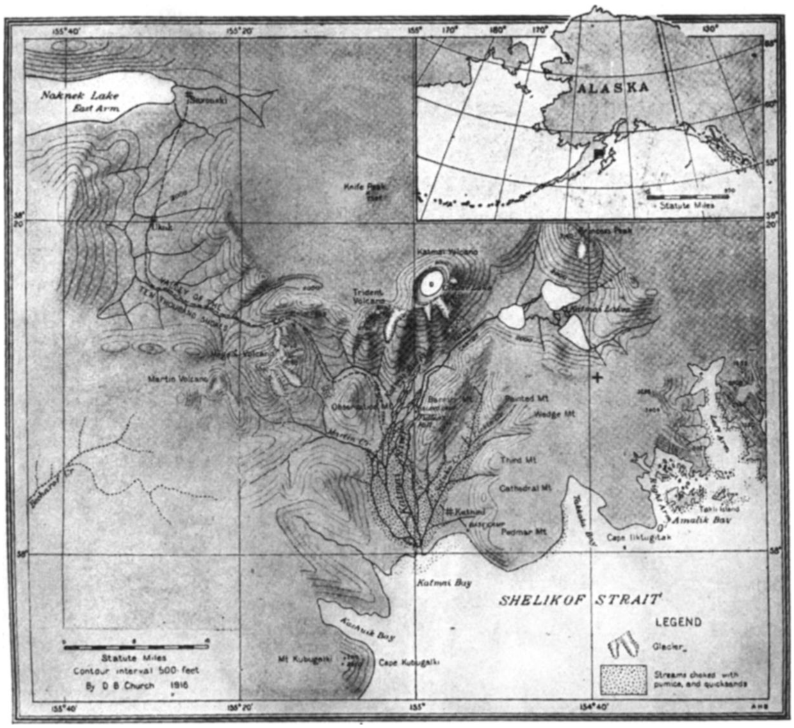

FIG. 1.—Sketch map of the Katmai region. By courtesy of the National Geographic Society.

In the Katmai country and its vicinity the volcanic mountains occupy a comparatively narrow strip of territory approximately parallel with the coast line, bounded on both the northwest and southeast sides by areas of predominantly sedimentary rocks. These sedimentary areas exhibit many forms of mountainous

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *Twentieth Annual Report, U.S. Geological Survey* (1898–99), Part VII, pp. 31–264.

relief, and the higher summits are but little inferior in elevation to those of the volcanic belt, but dissection has here reached a stage at which broad valleys of moderate slope have been developed.

The line along which arise the active or recently active volcanoes is one of the longest and most clearly defined volcanic chains in the world. At its northeast end the farthermost volcano whose character is definitely known is Mount Redoubt, though Mount Spurr, Black Peak, and Double Peak, from their position and characteristics, appear to prolong the range still farther to the northeast. These all lie well in the interior, among characteristically conti-

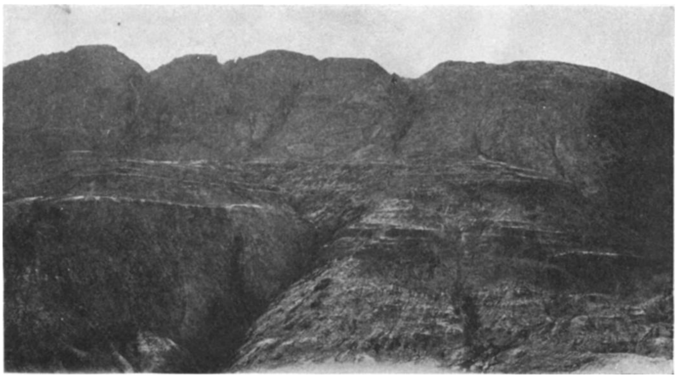

FIG. 2.—The Katolinat Mountains, between foot of Valley of Ten Thousand Smokes and head of Naknek Lakes. These mountains show sections of Upper Jurassic shale and sandstone, several thousand feet in thickness, in horizontal strata. Postglacial canyon in foreground. Photograph by J. D. Sayre, 1918.

nental structural features. Thence the range runs southwestwardly to the base of the Alaska peninsula, and follows the latter throughout its length. Here its course lies through a region of nearly horizontal sediments at only a moderate distance from the edge of the continental shelf, but where, at about the end of the Alaska peninsula, the edge of the shelf curves to the northward, the line of volcanoes continues without deviation and strikes off across oceanic deeps of 1,000 to 2,000 fathoms. The Aleutian Islands and their volcanoes form the summits of a narrow, steep-sided ridge, with great depths of water on both sides. The well-defined character and continuity of this volcanic belt were noted by I. C.

Russell, who says: "This belt of igneous activity is nearly 1,600 miles long. . . . . It is so narrow and well defined that two parallel lines drawn on a map of Alaska, twenty-five miles apart, may be made to include nearly every volcano in the belt that is known to have been active in historic times."[1]

It seems that such a linear distribution must indicate a major fracture in the earth's crust, and we might expect to find plain

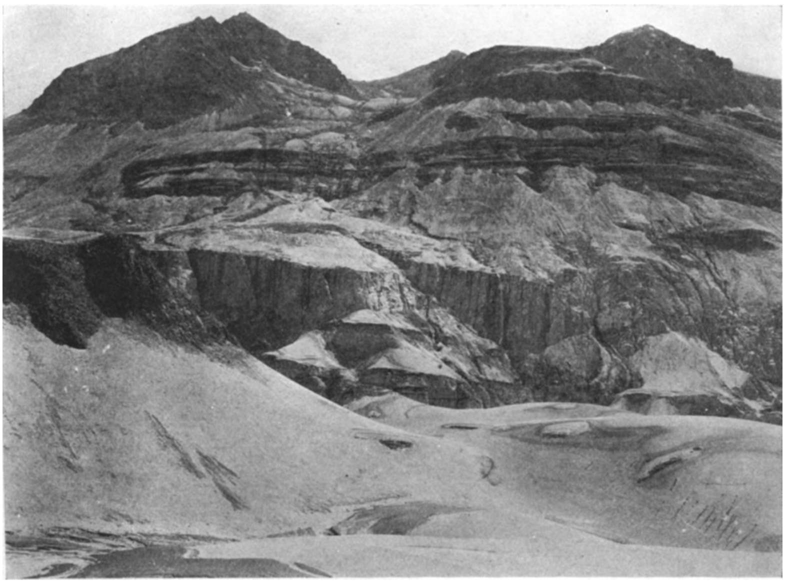

FIG. 3.—View across canyon of Katmai River, from lower slopes of Mount Katmai, looking at Barrier Range. These mountains consist of shale and sandstone, believed to be of Upper Jurassic age, in beds gently inclined away from the observer, with some igneous intrusives. Photograph by D. B. Church, 1916.

evidences of dislocation of strata or even profound disturbances associated with it. On the contrary, very little evidence of this kind is apparent in the region explored by us. On the northwest side of the belt masses of Upper Jurassic sediments (Spurr's Naknek series), 5,000 feet at least in thickness and possibly much more, lie in horizontal, undisturbed strata, whose continuity may often be

[1] I. C. Russell, *Volcanoes of North America*, p. 268.

followed by the eye for miles along the mountain sides. A typical mountain block of horizontal sediments is shown in Figure 2. On the southeast side of the range the sediments are still the shales and sandstones of the Upper Jurassic, little different lithologically or paleontologically from those on the other side. Structurally, however, this fact is observable—that they dip fairly uniformly away from the range at angles of 10 to 15°. Some typical views

FIG. 4.—Looking up canyon of Katmai River from Prospect Point. On the left, Mount Katmai in the background, and its lava slopes and cliffs in the middle distance; on the right, the sediments of the Barrier Range. Just above the river level and at the foot of the lava cliffs, surfaces of glaciated sandstone (shown in Fig. 5) were found. Photograph by D. B. Church, 1916.

are shown in Figures 3 and 4. This difference of attitude of the beds on the two sides of the range may indicate block-faulting and tilting, but this seems remarkably slight evidence to be the only indication of a break of such great length and reaching to profound depths. That profound depths have been reached is indicated by the manner in which the break extends without deviation across fundamentally different surface structures. There is, however, a possibility that the volcanic chain may be situated not directly along the surface trace of the major fracture, but

along a system of accompanying breaks. Such a relation appears to be not uncommon in other volcanic districts.

The Katmai group of volcanoes has evidently been built up on a platform of Upper Jurassic sediments, and several features show that comparatively recent flows have produced marked changes of topography. For instance, the canyon of Katmai River (shown in Fig. 4) is a narrow defile connecting open valleys above and below. It is evident that a former open valley here was invaded by floods of lava coming down from Mount Katmai, which shifted

FIG. 5.—Lava flow of basic andesite overlying glaciated sandstone and a small remnant of till (at pick), at foot of the lava cliffs shown in Figure 4. Photograph by R. F. Griggs, 1919.

the river over upon the lower slopes of the Barrier Range. The river has again cut nearly to grade along a narrow canyon, and beneath the lava-flows may be seen beds of till and sandstone surfaces grooved and polished by glacial action (Fig. 5). In this vicinity lava-flows of apparently post-glacial age measure 1,500 to 2,000 feet in thickness (see Fig. 4).

The lavas of the group of cones that we are considering seem to be predominantly basic andesites. In Mount Katmai itself the succession of flows that have built up the cone is now revealed in the great crater pit, and they appear to be of medium to basic character. The fragments of old rocks thrown out with the new lava in the

recent eruption are likewise of this composition, as are also the materials composing the bowlder beds at the rim of the crater (which probably represent a ground moraine whose components were transported by glaciers from the now annihilated upper slopes of the mountain). The testimony from all sources is concord ant and demonstrates with a reasonable degree of certainty that Katmai is predominantly andesitic throughout.

In addition to the lavas that have built up these cones, however, there seem to have been other products thrown out by them. In several places near the lower end of the Valley of Ten Thousand Smokes recent stream-cuttings show peat beds interstratified with many narrow bands of siliceous pumice. Probably the rhyolitic lava ejected in the latest eruption of Katmai was not the first highly siliceous differentiate evolved from the underlying magma.

THE VALLEY OF TEN THOUSAND SMOKES AND ITS GREAT ASH DEPOSIT

According to Spurr's description the portion of the Katmai trail immediately to the northwest of the Pass ran for several miles through a wooded valley of varied topography. During the activities of the eruption, the floor of this valley was covered with a thick deposit of ash and pumice, which in most places has buried every detail of the former topography, and whose surface now forms a gently sloping plain. Thousands of fumaroles have found vent through this deposit and are sending out exhalations of hot gases and vapors. Professor Griggs, who discovered and described these remarkable features, has given to this valley the name "Valley of Ten Thousand Smokes" (Figs. 6 and 7).

This ashy deposit covers the old floor of the valley to a great depth (possibly several hundred feet in certain areas) and extends up over Katmai Pass. Its distribution is shown on the map of the valley.

From the very first explorations of the region by the National Geographic expeditions, Professor Griggs recognized that this deposit is quite distinct from the widespread ash-falls due to the explosive ejection of material from Katmai crater, and that it must be accounted for by the operation of other processes. Because of the fact that, when first discovered, certain of its characteristics

were thought to imply that its formation was the result of the extrusion of a mass of semi-fluid mud, this deposit was termed "the great hot mud-flow," and has been so described.[1]

To the Geophysical Laboratory members of the 1919 expedition the evidence seemed opposed to the idea connoted by the term

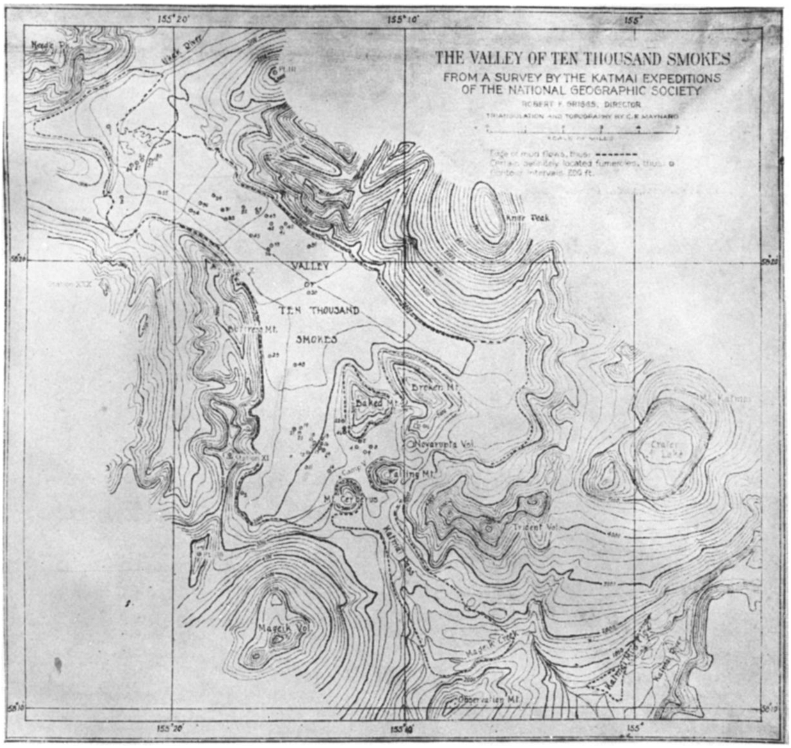

FIG. 6.—Topographic map of the Valley of Ten Thousand Smokes and adjacent region, from surveys made by topographers of National Geographic Society's expeditions.

"mud-flow," and early discussions among us led to the expression of the opinion by Dr. Zies that the evidence was much more in harmony with the idea of the movement of a dry, highly heated mass of sand and pumice than of a water-bearing mud. This

[1] Professor Griggs's article in the *Ohio Journal of Science* (Vol. XIX [December, 1918] No. 2, p. 117) gives an interesting description of this deposit and its remarkable features.

suggestion seemed from the first to have decided merits and later investigations served to strengthen it. Moreover, as evidence of various kinds accumulated, a much more complete conception of the attendant processes was afforded.

The make-up of the deposit itself, its situation with respect to the configuration of the landscape, and various striking effects produced by it demand that certain definite characteristics should be attributed to it at the time of its appearance, and prescribe

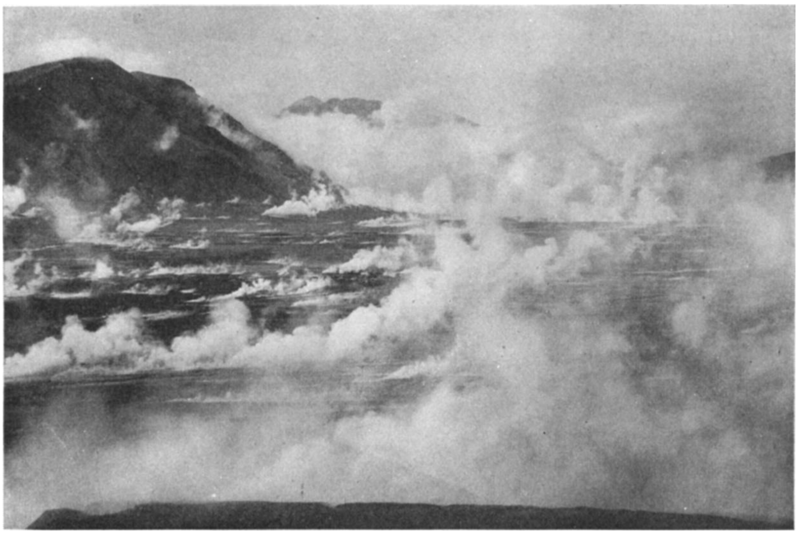

FIG. 7.—Looking northerly down the Valley of Ten Thousand Smokes. Photograph by R. F. Griggs, 1917.

rather rigid limitations to one's ideas as to its possible derivation. Observations show plainly that, in the first place, this material was not thrown violently into the air to descend over the general landscape, but that it was restricted very definitely to topographic depressions. In point of time, it was one of the first manifestations of activity, for it is covered by the subsequent ash-falls. The thorough manner in which vegetable material engulfed by it was carbonized and the indications of brush fires started by it can hardly be explained except on the supposition that it possessed a high temperature, probably near incandescence. In many places

adjacent to it but beyond its borders, fallen trees lie as if overthrown by a violent wind accompanying it. This is observable along the margin of the deposit and also on those slopes of the Katolinat Range that lie at the foot of the valley and face up the valley in the direction from which the flow advanced.

Katmai crater could hardly have been its source, as physical obstacles stand in the way of distribution from that point, and

FIG. 8.—The great sand-flow of the Valley of Ten Thousand Smokes, overlain by stratified ash from the Katmai ash-fall; view taken at junction of Knife Creek (at left) and River Lethe (at right, nearly concealed by steam cloud). The stratified terraces just above stream-level are not part of the sand-flow but are the result of recent stream deposition. Photograph by E. G. Zies, 1919.

glaciers that still cover the slopes of Katmai on this side would probably show noticeable effects from the movement of such an incandescent avalanche over their surfaces. The distribution of the material is such that there seems to be almost no escape from the conclusion that it originated within the valley itself and that we must look for its source in vents situated on the floor of the valley or on the lower slopes of the mountains at its head. Such

vents, however, would tend to be concealed by the material that they themselves extruded and by later materials from the ash-falls, and we are not able to point out the exact location of such vents with certainty. It is rather by a process of deduction that our opinions as to their position have been reached.[1]

The vents of extrusion may well have been located along the fissures that are now the seats of fumarolic activity. Support is

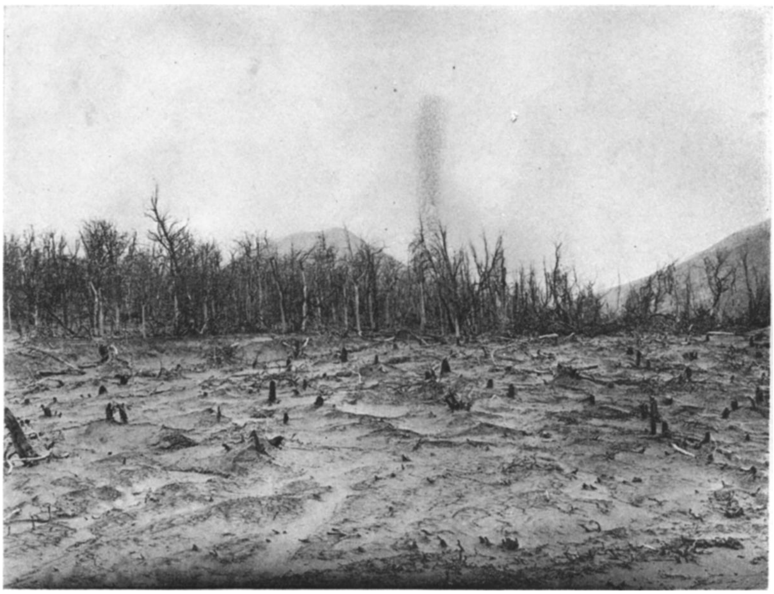

FIG. 9.—Carbonized stumps and tundra. The foreground was covered by the sand-flow, but the standing trees in background were beyond its reach. Photograph by E. G. Zies, 1919.

given to this supposition by evidences of former more vigorous activity of a mildly explosive kind at some of these localities. Possibly the newly formed crater of Novarupta in the upper part of the valley was one of the vents, differing from the others only in that it was of larger size than most and that its activity con-

[1] Professor Griggs had previously, in one of his articles, expressed the opinion that the material must have been extruded from fissures within the valley. See article, "The Great Hot Mud Flow of the Valley of Ten Thousand Smokes," by R. F. Griggs, in *Ohio Journal of Science*, Vol. XIX, No. 2, p. 139.

tinued into a stage not represented elsewhere, by which a plug of viscous lava was extruded.

Views of this sand-flow or sand-avalanche and of some of the effects produced are shown in Figures 8–10.

Considering further the origin of the sand-flow, we suppose that rhyolitic magma, charged with dissolved gases, rose to the surface in the newly formed vents. According to general observation the usual course for such a magma is either to retain its gases and form a flow of obsidian, or to evolve them with explosive violence and scatter the disrupted particles to a great distance. In this

FIG. 10.—Trees prostrated as if by wind accompanying sand-flow, though beyond reach of the avalanche of sand itself. Photograph by C. N. Fenner, 1919.

instance, however, it apparently pursued an intermediate course, and produced, by moderately forcible disruption, an outward-spreading and forward-moving torrent of incandescent sand and pumice, each particle of which was surrounded by and partially suspended in gases which it continued to give forth during its impetuous flow.

An artificial reproduction of the properties that are believed to have characterized this ashy material at the time of its extrusion may be obtained by igniting the powder of basic magnesium carbonate. The substance boils in a manner extraordinarily like a liquid, and the gases evolved buoy up the solid particles. In this

condition the mixture exhibits the lack of coherence and readiness to flow that characterize liquids.

The exact counterpart of this deposit does not seem to have been described among volcanic phenomena elsewhere, but the avalanches of incandescent sand and ash that formed prominent

FIG. 11.—Specimen of banded pumice (4×4 inches) from the deposit in the Valley of Ten Thousand Smokes. Adjacent bands show marked differences in composition, as indicated by a silica content of 74.70 per cent in the case of a light band, and 60.40 per cent in an adjacent dark band. The structure is believed to be due to digestion of foreign material.

features of the eruptions of Pelée and La Soufrière in the Antilles in 1902 seem to offer many close analogies. The following quotation from the *Encyclopedia Britannica* gives a statement of the essential features that have been observed in the Peléan eruption:

Its distinctive character is found in the sudden emission of a dense black cloud of superheated and suffocating gases, heavily charged with incandescent dust, moving with great velocity and accompanied by the discharge of immense volumes of volcanic sand, which are not rained down in the normal manner,

but descend like a hot avalanche. . . . . So much solid matter was suspended in the cloud, that it became too dense to surmount obstacles and behaved rather like a liquid.

Though one may find in the detailed descriptions of these sand-avalanches certain differences from the results seen in the area of the valley flow, they seem to be of degree rather than of kind, and the analogies are striking.

Some of the pieces of pumice in this deposit show a banded or variegated structure, such as is illustrated in Figure 11. The difference of composition of adjacent bands is easily apparent, and in the specimen figured, determinations of silica by Dr. Allen have shown 74.70 per cent in a white band and 60.40 per cent in a dark band. It is believed that these structures are due to a process of partial solution of basic rock in the new siliceous magma. The very limited degree of mixing of solutions shown by these specimens hardly permits us to suppose that the solvent action was long continued; therefore we must look for the source in matter which became involved in the magma when it was near or at the surface and just prior to its foaming-up into pumice. There are several possibilities that should be considered. We might suppose that the sedimentary series beneath the valley had been previously injected by rocks of this description and that these were encountered by the new magma and material absorbed from them; or that the floor of the valley was composed of an old lava flow of basic composition, which contributed material; but the supposition that, for a number of reasons, appears to me the most probable is that the source to which we should look is the deposit of lava bowlders of glacial origin that covered the floor of the valley to a great thickness. The fragments of undissolved andesite found with the ash are probably of the same origin, while the pieces of shale that are quite common in places were doubtless derived from the underlying Naknek sediments. All of these may be duplicated in the lava and ejecta of Novarupta.

THE FUMAROLES

The fumaroles, which are now the most active volcanic features of the region, usually find vent through the unconsolidated deposits

that cover the floor of the valley. In most places they are restricted to the valley floor and few are found on even the lower slopes of the adjacent mountains, but the country within a radius of a mile and a half of Novarupta forms an important exception. In this area, hill and valley alike have been greatly shattered, and are crossed by many steaming fissures. This includes not only the portions of the valley to the east and west of Novarupta, but also Baked Mountain, Broken Mountain, Falling Mountain, and some of the lower slopes of Trident. This area was undoubtedly a scene of the greatest activity during the eruption and is still the site of many fumaroles. Evidently the strains that were here set up in the outer crust have been of sufficient magnitude not only to cause fissures to break through the valley floor but also to shatter the adjacent mountains. In most places, however, they are so restricted to the floor that this topographic depression was evidently a controlling factor, and hence a moderate depth for their place of origin is implied. The phenomena suggest what might be expected from the injection of a sill under a rather small thickness of cover.

The fumaroles were the chief subject of investigation by Dr. Allen and Dr. Zies. They made many measurements of temperatures and collected samples of gases for analysis, and much of interest may be expected when their work is completed. At present the account will be confined to a slight description of a few of the features of the fumaroles. In temperature they run from below the boiling-point of water to a heat more than sufficient to melt lead and zinc. The highest temperature found was 645° C. Among the evolved gases, water usually forms more than 99 per cent. The remainder is mostly hydrogen sulphide, nitrogen, carbon dioxide, and methane. Hydrochloric and other acids are probably present, though in small amounts.

Around the vents sulphur is often found in quantities as a sublimation product, and pyrite in finely divided form is very common. Ammonium chloride also has been collected, as well as crystallized hematite and magnetite, and study of the crusts brought home will probably reveal other fumarolic sublimates. The vents are frequently alined along fissures half a mile to a mile

in length. The velocity of the outpouring gases is seldom very high; commonly their escape is attended by a hissing sound at small vents and a subdued roaring at large ones. A close view of a vent of moderate size is shown in Figure 12. It should not be inferred that all of the water that is evolved is of magmatic origin. The ashy and pumiceous material that forms the upper part of

FIG. 12.—Fumarole No. 42. Baked Mountain and Broken Mountain in the background, and the volcanic range in the far distance. Photograph by E. G. Zies, 1919.

the conduits is soaked with water, and considerable quantities must be vaporized and carried out with the hot gases.

FALLING MOUNTAIN

In the upper part of the valley and not far from Novarupta is Falling Mountain, so called from certain remarkable phenomena which it exhibits. Its northerly face is an almost cliff-like slope, probably 2,000 feet in height, which has plainly been produced by recent slumping off of masses of rock. The volume of material thus removed must have been enormous. At the present time blocks or small masses of rock drop off at short intervals and plunge down the slopes with a succession of sharp crashes, and a

talus pile of considerable size has been built up by such accumulations, but this is of insignificant magnitude in comparison with the total quantity that has been lost to the mountain. Strangely enough, there is little hint as to what has become of this mass of rock. The mantle of ash and pumice that covers the floor of the valley at the foot of the mountain spreads its smooth contours over the whole surface. I think we must conclude that the great rock-avalanche at Falling Mountain was one of the first events accompanying the recent outbreak of volcanic activity, and that it occurred under such conditions of forcible disruption and violent movement that the material was spread widely over the valley floor. The subsequent deposits of ash and pumice, which here are of very great thickness, smoothed out the irregularities left in the surface of the transported material. The rock-falls that we now observe are probably of the nature of after-effects. Remnants of the fissures that were formed at the time of the original disturbances now afford passages for gases and vapors from below. Along these channels the andesitic wall-rock has been powerfully acted upon and transformed into porous aggregates of new minerals, whereby the rock rapidly loses its cohesive strength. It is not surprising to find that among the new minerals tridymite is prominent. The conditions are those under which its formation (as a metastable product) is to be expected. A noticeable effect also is the replacement of many of the pyroxene phenocrysts by aggregates of hematite scales.

These alterations seem to be explicable only on assumptions of rather wide-reaching significance. Apparently the gases that permeate the rocks and that manifest themselves at the surface by the slowly rising vapor clouds are capable of reacting with the constituent minerals in such a way as to form volatile compounds, and the porosity indicates that quantities of material have actually been removed by gaseous transfer. The results of similar processes are visible around the vents of many of the fumaroles on the floor of the valley. Here also there is evidence of the transportation of material in the gaseous medium, and we observe the results of reactions induced by rapidly changing conditions of temperature and composition as the gases approach the

outer surface. The most striking result is the deposition of iron compounds around the vents and in the steamy areas—pyrite, hematite, and magnetite—in quantities which, from the observations of Dr. Allen and Dr. Zies, must be very great in total amount.

When there is brought before us in such striking fashion evidence of the ability of these volcanic gases to transport material, we are naturally led to a consideration of the various circumstances attending the evolution of such gases and the effects that are likely to be accomplished. One query that arises is as to the results of the continual outpouring of such great volumes of vapor as rise from the neighboring peak, Mount Martin, and we may ask whether significant changes of composition are not thereby effected in whatever material may lie at the source from which this vapor proceeds, whether it be a body of magma or material of another sort. Unfortunately, insufficient knowledge of the composition of gases rising from the actual throat of a volcano, as well as of their amount and the length of time over which their escape continues, involves the subject in so much uncertainty that definite conclusions as to the quantitative importance of this process are, as yet, hardly warranted.

THE NEW VOLCANO NOVARUPTA

Near the head of the Valley of Ten Thousand Smokes is the site of Novarupta, a small parasitic vent, which evidently was an exceedingly active volcano during the general eruption, and threw out great quantities of fragmental material, chiefly pumice. Much of this is in much larger masses than those thrown out by Katmai. One such projectile, found about a quarter of a mile away, had a diameter of eight feet. The last act of the vent was to extrude a mass of stiff, viscous glass, which, as it was slowly thrust upward, broke into huge blocks. From a distance this pile of steaming lava-blocks, which is about 800 feet in diameter and 200 feet high, resembles an enormous ash heap. It is surrounded by a circular crater-wall composed of ejected fragments, which is much cut up by actively steaming fissures (see Fig. 13). The material of this is mostly pumice and obsidian, but there are also pieces of shale and sandstone and of dense andesite. The question as to the

manner in which this new vent was developed in the floor of the valley is important. There are undoubted evidences of explosive action, but nothing that may not well be attributed to actions going on after the vent had been opened. What we have to account for here is the formation of a rather small, circular orifice, through which a great amount of pumice was ejected and a small amount of lava was extruded, situated in an area which is much

FIG. 13.—Profile of lower part of Novarupta, and a portion of the inclosing crater wall. Photograph by P. R. Hagelbarger, 1918.

fissured but in which other vents of comparable size are lacking. The formation of an orifice of this description is sometimes attributed to the assumed ability of a subterranean body of magma to perforate by explosive action a great thickness of overlying strata and form a cylindrical pipe or conduit (diatreme) for the escape of lava. It is difficult, however, to form a conception of the manner in which such action has been carried out without attributing to the magma properties for which the evidence seems insufficient. It would be necessary to assume not only that an enormous

amount of energy is set free with great suddenness in a narrowly confined space, but that in some manner this force is given a definitely directed tendency upward. The inherent difficulties in this conception are so great that we naturally look for a simpler explanation.

We might suppose, as a second possibility, that the underlying magma possessed great expansive powers because of dissolved gases which were struggling to escape, and was thus enabled to effect an upheaval of overlying material, but the natural result of this would be the upturning of huge blocks over a rather wide area, and the escape of pumiceous material from many widely open fissures, accompanied by the ejection of portions of the fractured blocks in large masses. No such evidence is visible around Novarupta. The ejection of pumice seems to have been confined mostly to a small opening, and there is no hint in the surface contours of the ash that a widespread chaotic upheaval of strata occurred. Moreover, the largest pieces of ejected sediments found were about the size of one's fist. We turn, therefore, to a third hypothesis, which is really the simplest of all: that fissuring was first produced, either because of regional strain or because of hydrostatic pressure due to the injection of a sill; and that the magma rose along such fissures in much the fashion that any liquid might do, except that a certain amount of solution was effected, and that near the surface a sudden conversion into pumice resulted in the violent abrasion of the walls. Under this conception Novarupta would simply represent a channel along one of the fissures, where chance conditions made escape specially favorable and which therefore tended to enlarge the conduit rapidly and establish more direct connection with the body of magma below. It will appear farther on in this article, as various topics are discussed, that none of the phenomena of the Katmai eruption seem to indicate that these magmas exerted great explosive or expansive powers at depths within the earth, and Novarupta conforms to this idea. Undoubtedly explosions of a violent character occurred here after the magma had reached the surface, but no evidence was found of such explosions prior to its ascent.

The banding present in the lava of the dome that now rises above the vent gives very direct evidence regarding the mechanism of its extrusion. This banding is visible at short intervals around the outer circumference of the dome, where masses of rock in place protrude through the general heap of disrupted blocks, and its direction is found to be parallel with the circular outline of the dome. There is also very good evidence of a process of exfoliation of the outer layers as the central core was forced upward.[1] The character of fracture surfaces of the lava-blocks of the dome is

FIG. 14.—"Cornice structure" in Novarupta lava, produced by fracturing and viscous yielding of the hot mass. Photograph by R. F. Griggs, 1919.

interesting. It shows that many of the fractures occurred while the glass possessed properties of both brittleness and viscosity, such as are shown by stiff tar. This resulted in effects of the kind shown in Figure 14, where the surfaces formed by intersecting fractures have become wrinkled and fluted. The term "cornice structure" suggested itself at once as appropriate for such features.

Many bread-crust bombs are found in the vicinity of Novarupta. These were ejected from the crater as masses of non-vesicular, plastic glass, and the vesicularity developed during the

[1] Compare Harker, *The Natural History of Igneous Rocks* (1909), p. 58, Fig. 8.

short interval of time in which the rapidly cooling mass possessed a rigid crust and a plastic interior. The point to be noted is that the magma, rising into the crater from the depths below, did not immediately puff up into pumiceous masses, but accumulated, at times certainly, in pools of non-vesicular lava. The surprising thing is that this condition held in spite of the relief of pressure. On the other hand, we have evidence that under certain conditions very great pressure did not avail to hold the gases in solution. This is furnished by the lava that was later extruded and now forms the dome. In spite of the enormous pressure to which this

FIG. 15.—Mount Katmai, from the Island Camp. The crater pit extends across nearly the whole space between the two summits. Photograph by R. F. Griggs, 1917.

was subjected during extrusion, the contained gases came out of solution and filled the glass with minute vesicles. The explanation of such phenomena as these will be undertaken later.

MOUNT KATMAI AND ITS EJECTA

Let us consider now some of the features of Mount Katmai, and first the form of the crater as it appears since the eruption. The present appearance of Katmai is shown in Figure 15. Before the eruption the height, as shown by the Coast and Geodetric Survey chart, was 7,500 feet. The top of the mountain has now disappeared and an enormous crater abyss has been formed.

Measurements made by Mr. C. F. Maynard, topographer of the 1917 expedition, give the dimensions of this pit as 2 to $2\frac{1}{2}$ miles in diameter and 2,000 to 3,700 feet in depth. About one-half of the area at the bottom is covered by a sheet of water of a peculiar, milky, turquoise-blue or green color, and from near the center of this lake rises a crescentic island. To one standing on the edge of the pit the cliffs appear almost vertical, but their inclination is probably not more than 60° to 70° on the average. They seem to be made up entirely of a succession of lava flows. On the western side of the rim, for about one-third of the circumference, an ice wall appears—a survival of beheaded glaciers, and the depression in the southern side of the rim is floored with bowlder deposits of morainal origin. The bottom of the crater, where not covered by the lake, appears from above approximately flat. At the foot of the cliffs are talus deposits, which appear of rather insignificant proportions. At present the activity is very slight. Steam rises slowly from a number of fissures and clefts near the bottom, and the water of the lake is evidently warm, but on August 10 snow was lying in many places on the crater floor.

The crater of Katmai is a most wonderful and impressive sight, and photographs give but a very inadequate idea of its tremendous proportions (Fig. 16).

A matter of great interest is that of the mechanism by which this huge pit was formed, for this is intimately related to the question of the volcanic processes attending eruptions. Professor Griggs had recognized the importance of solving this problem and had called particular attention to it before our departure for the region. One's first view would naturally be that the material was blown out bodily in the eruption, but there is good evidence that this is not the whole explanation. A remarkable characteristic of the ejected material is the small dimensions of the fragments. Even on the upper slopes of the mountain there are not many pieces above the diameter of a few inches, and a great proportion of them are much finer. Moreover, almost all the larger pieces are of pumice, and the fragments of older rock have a general maximum size even less than the figures given. Also the proportion of these older andesites is rather small, not nearly sufficient

to account for the mass that has disappeared. Their presence is not likely to be overlooked, as their color—dark red to nearly black—renders them conspicuous objects among the accumulations of light-gray pumice. Since this explanation will not account for the total mass of rock that has disappeared, two other possibilities should be considered: first, solution of the older rock in the new magma; and second, crater subsidence.

Respecting solution, it is believed that this process was very active. That this had occurred was suspected several years ago, as specimens of pumice collected by Professor Griggs on former

FIG. 16.—The crater pit of Katmai. Topographic measurements indicate a diameter of 2 to 2½ miles, and height of cliffs as measured from the level of the lake as 2,000 to 3,700 feet. Photograph by J. D. Sayre, 1919.

expeditions had been examined microscopically by Professor W. J. McCaughey, of Ohio State University, and the presence of basic phenocrysts in the acid magma and the evidences of instability that they manifested had been noted by him. This has now been confirmed independently and much additional evidence has been secured. Various stages of digestion can be followed until the point is reached where quantities of phenocrysts of hornblende, pyroxene, magnetite, and rather basic feldspar are left undissolved in the glassy matrix. In such instances the original groundmass of the basic rocks has been completely dissolved and the phenocrysts are corroded. Plainly such phenocrysts are out of place in

a rock of the composition of that in which they are found. Moreover, pieces of banded and variegated pumice are common, such as those previously described as occurring in the Valley of Ten Thousand Smokes (see page 583), and are attributed to solution of basic rock in the new siliceous magma just prior to ejection. The evidence on these matters will be discussed more fully a little farther on. It appears to show that the new magma, when it rose into the crater, possessed a sufficient degree of superheat to cause it to attack corrosively the basic rock of the crater walls, and, within a brief period, to effect sufficient solution to permit the dispersal throughout its own mass of the basic phenocrysts derived from great quantities of foreign rock-material. The heat requirements seem to demand that in addition to the original store large accessions should have been received, possibly from rising gases.[1]

In any case a new synthetic magma is believed to have been formed in large quantities. The rapidity of destruction of the walls would be attributed to a combination of the shattering effect of explosions and the corrosive action of magma lying in a pool in the crater. The disappearance of much of the rock of the walls may thus be accounted for. Whether all of it may be accounted for by this process and by the ejection of fragments of undissolved rock is not certain. Further evidence will be obtained from analyses (which Dr. Allen has undertaken) of selected material representative of the new magma, little affected by digestion of basic rock; and of other material, representative of the average result attained by the digestion of foreign matter.

The alternative hypothesis, that of crater subsidence, is one in regard to which little or no direct evidence has been observed. Apparently rock-slides of considerable importance have occurred at several places in the crater, due to the failure of the vertical

[1] Daly's discussion of the effect of rising gases (*Igneous Rocks and Their Origin*, p. 267) is rather misleading. It is true that a bubble of gas, expanding and doing work, loses energy approximately equivalent to the work done, but if the work be expended in producing viscous flow in the surrounding magna, the energy lost by the gas is taken up by the magma, and the system as a whole neither gains nor loses. We may therefore disregard expansion and look upon gas rising from below into a cooler region as a source of heat.

cliff-walls to support themselves, but this may be quite independent of a general subsidence of the floor of the crater. We know from Martin's account[1] that natives who had apparently fled from the region almost at the beginning of the activities reported that the top of the mountain was gone. We should hardly expect crater subsidence to take place at this early stage. On the whole, it seems that this idea should be applied only if the process of solution, which, in any case, seems to have occurred on a large scale, appears quantitatively inadequate to account for all the material that has disappeared. At present it seems best to postpone judgment on this until more information is obtained from the analyses.

EVIDENCE AS TO THE NATURE OF THE ERUPTIVE PROCESSES

A study of the ejecta from Katmai and of the characteristics of the deposits that they form supplies considerable additional information on the eruptive processes. When seen in undisturbed deposits at a distance of, say, eight or ten miles from the crater, the ejected matter forms well-defined strata, such as are shown in Figure 17. The component material is chiefly a light-gray pumice in pieces whose dimensions are three to four inches as an ordinary maximum, and run from this to a very minute size. Mingled with this are specimens of banded pumice, dense obsidian, stony andesites, sedimentary shales, and a sort of volcanic conglomerate. Some of the features of these, and their significance, have been touched upon before but will now be considered in more detail.

It was pointed out, in discussing the great sand-flow in the Valley of Ten Thousand Smokes, that the banded and variegated character of some of the pumice indicated a mixture of basic material with the new siliceous magma shortly before extrusion. In such specimens, sharply defined bands adjacent to each other show such differences of composition as are indicated by Dr. Allen's determination of 74.70 per cent silica in one and 60.40 per cent silica in another. The material thrown out from Katmai crater contains similar specimens. The dark bands consist of partly digested basic rock with large quantities of minerals appropriate to andesites.

[1] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV (February, 1913), No. 2, p. 147.

A lack of homogeneity on a somewhat larger scale is indicated by the fact that pieces of pumice from the same stratum of the ash-fall show considerable variation from one to another in the amount of basic phenocrysts they carry. These features are significant. It seems as if turbulent motion in the lava when it was liquid would have destroyed such inhomogeneities, especially the sharply defined banding; hence, that solution occurred subsequent to the

FIG. 17.—The stratified Katmai ash-fall, 8 to 10 miles south of the mountain. Note the sharply defined character of the strata. The heterogeneous material on top is the result of a small landslip since the deposition of the ash and pumice. Photograph by B. B. Fulton, 1915.

rise of the lava and while it was standing in a pool not violently agitated. Evidently the magma did not become inflated at once when pressure was removed in the depths of the earth, but rose as a liquid and stood for a certain period in contact with foreign material upon which it acted corrosively.

A careful study has been made to determine the probable source of this basic material. From samples of the ashy strata taken in the field the pumiceous portion, which is greatly preponderant, has been separated. The residue is found to consist principally of

dark, dense material in small fragments. These, to the number of hundreds, have been studied under a binocular magnifier. Their indentification has not been difficult. Sediments excluded, they consist usually of andesites containing small phenocrysts or groups of phenocrysts of plagioclase, hornblende, pyroxene, and magnetite in a felsitic groundmass. In some, however, the phenocrysts are absent. Most are dense but some are vesicular. In microscopic section the small feldspars of the groundmass are frequently seen to be arranged in flow-lines. It is evident that some of the specimens belong definitely to surface types of rocks and all of them may well be such. The possibility that hypabyssal rocks also may be present cannot be wholly excluded, but no evidence of this origin for any of them has been recognized. In composition they are medium to basic andesites, apparently no different from the rocks that form the walls of the crater pit.

Evidence is at hand regarding the absorption of these andesites by the new magma, but before we proceed to consider this matter it is necessary to digress for a moment.

As previously indicated, it is supposed that the fragments of andesite found in the ash-fall, or at least a large proportion of them, represent wall-rock that collapsed and became immersed in the pool of lava. One might expect, therefore, that similar pieces would frequently be found as inclusions in the pumice. This does not seem to be the case· on the contrary, their mode of occurrence is nearly always as detached particles. This is a matter that requires examination, and several features have been noted which have a bearing upon the subject. It is found, first, that not only are inclusions of andesites rare in the pumice but likewise inclusions of shale and of all other dense material except the phenocrysts; second, many of the fragments, although not now inclosed in pumice, present evidences of previous immersion, such as films of glass adhering to their surfaces, and corrosion effects; third, although the pumice does not carry inclusions, the obsidians, which must have been derived from the same lava-pool as the pumice, carry great quantities of both shale and andesite. From these facts it seems that the conclusion to be drawn is not that the andesites were never immersed in the magma, but that, in

the violent explosions, the frothy, semi-liquid pumice and the dense, rigid andesites reacted differently and were forcibly torn apart. The forms of many of the fragments of andesite are such as to suggest fracture by the explosions. If the forces acting upon them were of such magnitude as to produce fracture, it hardly seems surprising that they became separated from the pumice.

Pieces of obsidian, of ordinary maximum dimensions of three to four inches, and of angular shape, were found everywhere in the Katmai ash-fall within the area of coarse ejecta. Many specimens were collected for study, and they furnish interesting information. It is difficult to conceive any origin for them other than the lava pool that gave rise to the pumice; and the presence within them of pieces of pumice (which would inevitably float on the lava) and their general nature suggest that they represent chilled crusts on the surface of the lava. They contain quantities of inclusions of various kinds: sediments, andesites, other obsidian, pumice, and separate crystals. If it be granted that they are fairly representative portions of the lava, the inclusions they contain "frozen in" in all stages of disintegration are of great instructive value.

Another material present in the ash-fall is evidently closely akin to this conglomeratic obsidian. The matrix is semi-pumiceous to glassy, and the numerous inclusions are of the same sort as those in the obsidian. It is interpreted as a surface scum formed over areas of seething lava. The inclusions in this also have been caught in various stages of disintegration.

From the evidence presented by these specimens, the absorption of xenoliths by the magma seems to have taken place in several somewhat different ways. The chemical composition of the fragments and their porosity were probably important factors in the matter. In some instances peripheral solution, especially of the groundmass, seems to have been the principal process, or well-defined tongues of lava may cut off portions and allow them to float away. Probably a more usual form of attack is one involving an intimate penetration of the whole mass. Several factors may have been involved in this: first, that portion of the groundmass of the rock that consolidated last of all and forms a binding-material

among the grains may have had a melting-range little above the temperature of the new magma, and the penetration of the latter and of its vapors was therefore easy; second, an original vesicularity may have been present; and third, a porous condition may have been developed during the history of the rock. The third feature is important. It is not hypothetical, but rests upon observation, and is believed to have considerable significance. It has been found that many of the andesitic fragments in the pumiceous strata have at some former time undergone a process of alteration similar to that described for the rocks of Falling Mountain. Quantities of minute, glistening scales of tridymite have been formed, and a replacement of ferromagnesian minerals by hematite is observable. This carries several implications: first, these mineral transformations are such as might be expected to result from fumarolic action along fissures in the walls of a crater, but not of the kind that would be looked for at great depths; second, the presence of such fissures and the mineral transformations along them would aid in the collapse of the walls during the activities of the eruption; and third, these altered rocks would be more susceptible to penetration by the magma on their immersion in it.

When the process of penetration of magma into porous xenoliths has been thorough, they appear to have become pasty throughout, and what we find is an irregular, lumpy mass, or clot, consisting of basic minerals in a dark groundmass. Under the microscope the phenocrysts are seen to be much corroded. They often contain a great number of inclusions of brown glass, which fairly riddle them, and they look as if they were disintegrating. The groundmass is essentially glassy but contains a multitude of small, irregular fragments or splinters of crystals, and much brown dust. The low index of this glass indicates an acid material in spite of the dark color, and it seems doubtful whether the amount of material actually fused or dissolved was large; the process was rather one of intimate penetration by the new magma, resulting in separation and dispersal of the component minerals and a partial breaking up of crystal units. The low silica-content found by analysis (as in the specimen illustrated in Fig. 11) and the dark color are probably due to undissolved phenocrysts and dust. When the

penetration by the magma reached a fairly advanced stage before the final inflation occurred, these dark masses as well as the light glass assumed the porous condition; both must have been charged with vapors.

Although, under some circumstances, the bands or schlieren that have arisen from these pasty masses remain sharply distinct for several inches and perhaps much more, it is not unusual, on the other hand, for bands to disappear within a short distance. The facility with which the banding has become obliterated in these cases shows that its sharp definition is not a property that persists in spite of turbulent movements.

In the pumice of the early strata of the ash-fall, phenocrysts are almost lacking; in later strata they become exceedingly abundant. Their appearance at this later stage is ascribed to the setting free of phenocrysts from the andesitic wall-rock in the manner described. Their character in the two environments has been carefully compared. Those in the andesites have been studied in microscopic sections, and also under a binocular magnifier in such specimens as show surface corrosion, which has left them in partial relief. The phenocrysts of the pumice have, many of them, been set free by explosions and occur loose in the ashy strata. These are easily studied with the binocular magnifier. Others, still inclosed within a matrix of pumice or obsidian, have been examined in thin sections. In the andesites the phenocrysts occur both as isolated crystals within the felsitic groundmass and as aggregates of the kind that Judd has called glomeroporphyritic groups, and have certain characteristics in regard to size, form, and grouping. The component minerals are pyroxene, hornblende, plagioclase, and magnetite. In the pumice we find the same minerals, isolated or in the same sort of groups as before, apparently duplicating in all respects the phenocrysts of the andesites.

Let us review briefly the evidence that has been presented on this matter. An immense amount of material has disappeared from the top of the mountain and from the crater walls, and must be accounted for. In the pumiceous strata fragments of andesites are found that have the characteristics of surface-flow rocks, and correspond to what is known of the rocks in the crater walls. The

evidence of fumarolic action that many of them bear is in accord with such a situation. These might account for the rock that has disappeared except that they are quantitatively insufficient. We are left, then, to consider crater subsidence versus incorporation in the new magma. Without trying to decide in this article whether *all* of the material may be accounted for by incorporation, the evidence that a large quantity has been taken up in this manner has been considered. According to this evidence, numerous specimens of andesite show attack. The processes involve either an intimate penetration and consequent softening of the whole mass, followed by dispersal of the phenocrysts; or the breaking up of the fragments by attack along fissures, simultaneously with solution of the groundmass around the periphery of the fragments and eventual setting free of the phenocrysts. Finally, multitudes of phenocrysts of the kind that the andesites carried are found to appear in the later strata of the pumice, though the earlier strata are practically free from them. Their instability with respect to their surroundings is indicated by the active disintegration that they are undergoing. The fact that quartz phenocrysts properly belonging to the magma have no association with them is also significant. These facts taken together seem to form strong evidence identifying the phenocrysts of the pumice with those of the former wall-rock, and the disappearance of large quantities of wall-rock is thereby accounted for.

Some of the materials in the ash-strata deserve further attention. The obsidians that have been described, when heated in the laboratory, swell up to a frothy white pumice closely resembling the pumice found in the field. When their powder is heated in a closed tube it yields water, hydrogen sulphide, hydrochloric acid or a chloride, and some gas having a fetid organic odor. It is planned to investigate these gases with care.

Although many phenocrysts of extraneous origin are found in the pumice, the only phenocrysts that properly belong to the magma are quartz and acid plagioclase. These had probably crystallized out before the magma rose into the crater. The quartz, which is easily recognized, is never associated with the groups of xenocrysts mentioned, but, on the contrary, is found in the purest rhyolitic

phases of the pumice. Its presence supplies information regarding the upper limit of temperature within the magma chamber just prior to extrusion. The transition point between quartz and tridymite at atmospheric pressure is 870° C. Probably great pressure will have a perceptible effect in shifting the inversion-point—a thickness of 20,000 feet of rock strata might possibly raise it 100°—but we can be fairly sure that a temperature of less than 1000° prevailed.

The distinctly stratified form of the ash-fall, with its indications of a waning and renewal of activity many times repeated, harmonizes with the other evidence presented that the melted rock accumulated in a pool in the crater rather than that it was discharged as a continuous stream as soon as some hypothetical obstruction, which had previously restrained its escape from the depths, was removed.

From the evidence that has been brought together certain deductions may now be made. We see that the magma, as it issued from the depths of the earth, did not at first show a tendency to evolve its gases explosively; that is, did not have an extremely high vapor-pressure; but that this was developed after a short period of standing under the new conditions, and explosive eruptions ensued. From this we conclude that in the enormous change of conditions consequent upon rapid extrusion internal equilibrium did not keep pace with external changes, and that prior to extrusion such internal combinations prevailed that the tendency of the gases to escape was not extremely great.

As an indication of the depth in the conduit at which explosions occurred the relative amounts of the various sorts of foreign material ejected with the pumice is of interest. Pieces of andesites from the crater walls are very common; fragments of shale and sandstone from the sedimentary platform are frequently found, but the quantity is not so great as of the andesitic rocks; and pieces of deep-seated granitoid rocks are almost lacking, though a few specimens were found. This relative abundance seems to show that the violently explosive action was exerted only at the surface or at a moderate depth in the conduit.

If the renewal of activity at this vent after a long period of quiet were due to an accumulation of imprisoned forces until they reached a magnitude where they were capable of blasting away

obstructions, the bottom layer of ejecta should be made up largely of material from such a source. As a matter of fact this bottom layer is essentially pumiceous and actually appears to be more nearly free of foreign material and more nearly of rhyolitic composition than any layer above it. The view that the close of a period of activity at a volcanic vent is attended by the formation of a plug of lava which seals up the conduit and that the renewal of activity necessitates the clearing out of such a plug, finds little to support it here. Nor, I think, does a consideration of events in certain other explosive eruptions lead to views different from those expressed for Katmai. Many instances might be cited in which for months previous to a paroxysmal eruption manifestations have occurred, such as outbursts of gas and ashes, that can hardly be looked upon otherwise than as indicating a quite direct connection between the surface and the subterranean activity. It seems not unusual, too, for lava to appear in the crater and remain comparatively quiet for a certain period before explosive inflation occurs. The great eruption at Krakatoa in 1883 seems to have followed such a course.[1] At Pelée also there were premonitory symptoms, consisting of an increased evolution of vapors, at times mixed with cinders; later the moderately explosive (though immensely destructive) ejection of the *nuées ardentes*, accompanying the rise of lava in the crater.[2] A somewhat similar course of events may be found in Koto's description of the eruption of Sakura-jima.[3] By what means a volcanic vent can remain sufficiently open to permit a free escape of vapors, without allowing magma to issue, and what conditions finally bring this period to a close and cause a body of gas-charged, actively corrosive magma to appear are matters whose explanation presents many difficulties. No theory of volcanism that I have seen appears at all adequate to account for the phenomena. Indeed, some of the fundamental concepts of current theories seem irreconcilable with them.

Objection may be raised to the somewhat novel idea that has been presented here, of a state of unstable equilibrium of the

[1] J. W. Judd, "The Eruption of Krakatoa and Subsequent Phenomena," *Report of the Krakatoa Committee of the Royal Society*, pp. 11–20.

[2] A. Lacroix, *La Montagne Pelée et ses Eruptions*, pp. 35–39.

[3] B. Koto, *The Great Eruption of Sakura-jima in 1914*, pp. 56–82.

magma, and the question may be asked as to what combinations are supposed to be entered into between the volatile and non-volatile constitutents that would give the required effects, also as to the nature of the changes in the physical environment by which the condition of unstable equilibrium is brought about. These are natural queries, and answers would be eminently desirable; nevertheless, it is believed that the case rests not upon the ability to answer them but rather upon the plain evidence of the phenomena themselves. It may be of assistance, however, to a comprehension of what is meant by unstable equilibrium of the magma, to consider certain familiar phenomena exhibited by obsidians. Any obsidian which, when heated, puffs up into pumice, shows characteristics allied to those that I have ascribed to the Katmai magma. The behavior of the obsidian in this respect indicates that it likewise in its past history underwent changes of condition in which internal equilibrium failed to keep up with external changes. If this were not true it could hardly have retained its dissolved gases but would have evolved them during cooling. In instances of this kind the lack of equilibrium continued even beyond the stage which the Katmai lavas reached, and finally all possibility of evolving gases disappeared because of increasing rigidity, but this result was probably due to factors (such as rate of cooling) which may well be variable. In the case of Katmai and other volcanoes, it seems reasonable to suppose that the magma first experienced very rapid change of conditions during its rise in the conduit, but then remained for a certain period in comparative quiescence, and thus opportunity was given for approximate equilibrium to be reached before a condition of prohibitive rigidity had set in.[1]

From evidence of the kind given it appears that examples of unstable equilibrium in magmas, due to sudden changes of environment, are not at all uncommon. Recognition of this fact and of what it connotes may be helpful in directing inquiry into the conditions that have brought it about.

[1] Interesting examples of the effect of rate of cooling upon the final product in somewhat analogous systems are furnished by Morey's experiments on hydrated alkali silicate melts prepared in steel bombs. Rapid quenching gave a rigid, hydrated, unstable glass, while slow cooling caused the expulsion of dissolved water and the formation of a pumice. See G. W. Morey, *Jour. Amer. Chem. Soc.*, Vol. XXXVI (February, 1914), p. 226.

SUMMARY AND CONCLUSIONS

A preliminary account has been presented of observations made by the writer as geologist of the expedition sent in 1919 by the National Geographic Society, in co-operation with the Geophysical Laboratory, to the Katmai region. As a result of this work many of the observations made by the director of previous expeditions have been confirmed and supplemented. With regard to one or two others, somewhat different interpretations are given in this article from those of previous publications, but it is believed that on these matters also all concerned are now in agreement. With respect to still other phenomena, which had not been previously described, evidence has been found that affords a basis for extending considerably our ideas respecting the processes at work during the eruption.

It has been found that the volcanoes of this region, which form a continuation of the Aleutian loop or festoon, are situated in an area of sedimentary rocks remarkable for the absence of folding or obvious faulting. The more recent lavas are basic andesites, contrasting greatly in composition with the highly siliceous rhyolite of the last eruption.

In the area of the Valley of Ten Thousand Smokes, it is believed that the injection of a sill or closely similar body of magma into the underlying strata at the beginning of the eruption caused shattering of the rocks above it, and these openings permitted the ascent of magma. The extrusion and inflation of this magma gave rise to a great ash- or sand-flow, analogous in many respects to the *nuées ardentes* of Pelée and La Soufrière, and led to the formation of the parasitic cone of Novarupta. The fumaroles are thought to be due to the continued evolution of volatile constituents from this body of magma. The development of the new vent of Novarupta is ascribed to the enlargement of a channel along one of the fissures. The later extrusion of the stiff lava forming the dome of Novarupta is found to have been similar in many respects to that of the "spine" of Pelée.

At Falling Mountain the most interesting features are those resulting from fumarolic action. Evidence of a process of solution and transfer of rock material in the gaseous medium was found

here, and the results of similar processes around the vents of the fumaroles in the valley were observable. It is suggested that the properties of the evolved gases indicated by this gaseous transfer may at times lead to results of great importance in volcanic processes.

A study has been made to determine the manner in which the top of Mount Katmai disappeared and the great crater pit was formed. It seems quite certain that the material was not blown out directly but must be accounted for otherwise. Crater subsidence may have been a factor, but it is believed that collapse of the crater walls and incorporation of the material in the new magma were chief features. It is recognized that the latter process demands a large quantity of heat for its accomplishment, and the magma evidently was not at a very high temperature prior to its ascent; therefore accessions of heat seem to be demanded. A considerable problem is thus presented, but it does not seem at all insuperable, and it is believed that the evidences of solution are so strong that they cannot be disregarded.

One of the important features of the eruption brings up for consideration a phenomenon to whose significance little attention seems to have been paid hitherto. It is that of a gas-charged magma gradually developing the explosive condition after some interval has elapsed subsequent to its ascent from the depths. The Katmai magma seems to have followed this course, and the phenomenon is apparently not uncommon. This is believed to have great significance and to imply changes of physical environment during its ascent, effected with such rapidity that internal readjustments were not able to keep pace with them. Many of the current theories of volcanism are based upon a fundamentally different conception of the nature and properties of the magma. It is thought that it may be advantageous in many cases to consider matters from the new standpoint here suggested.

In other matters also, theories that have been proposed and somewhat widely accepted are apparently not in accord with the evidence found here. It has not been possible in this article to discuss these matters exhaustively, and other matters of interest have not been touched upon. Fuller treatment will be presented in articles to follow.

July, 1920